

Bioinspired Engineering of Exploration Systems

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**Bio-inspired Engineering of Exploration Systems 2000
held Dec 4-6, 2000 at Jet Propulsion Lab, Pasadena, CA**

BIOINSPIRED ENGINEERING OF EXPLORATION SYSTEMS (BEES)

- **WHAT ARE BIOMORPHIC EXPLORERS?**
 - **DEFINITION**
 - **BACKGROUND**
 - **BEES: SUB ELEMENTS/CATEGORIES**
 - **BIOMORPHIC SURFACE/SUBSURFACE SYSTEMS**
 - **BIOMORPHIC ADAPTIVE CONTROLLER**
 - **BIOMORPHIC FLIGHT SYSTEMS**
- **WHAT ARE BIOMORPHIC MISSIONS?**
 - **DEFINITION**
 - **COOPERATIVE LANDER/ROVER - BIOMORPHIC EXPLORERS**
 - **ASTRONAUT LAUNCHED BIOMORPHIC EXPLORERS**
 - **ENABLING PROCESSOR FOR SURFACE FEATURE RECOGNITION**
 - **BIOMORPHIC COOPERATIVE BEHAVIORS**
 - **BIOMORPHIC COMMUNICATION AND NAVIGATION**
- **SCIENCE APPLICATIONS AND PAYOFF**
- **PROGRAM OUTLINE AND ROADMAP**

BIOMORPHIC EXPLORERS

- **A MULTIDISCIPLINARY SYSTEM CONCEPT FOR SMALL, DEDICATED, LOW-COST EXPLORERS THAT CAPTURE SOME OF THE KEY FEATURES OF BIOLOGICAL ORGANISMS**
 - Small... 100-1000g (useful space/terrestrial exploration functions are implementable* using this mass)
- **CONDUCTED WORKSHOP, AUG 19-20, 1998**
 - **SPONSORED BY NASA/JPL**
 - **WEBSITE: <http://nmp.jpl.nasa.gov/bees/>**
 - **AN ENTHUSIASTIC RESPONSE: OVER 150 PARTICIPANTS**
- **JPL INTERNAL DOCUMENTS: D-14879A, D-16300A, D-16500,
AUTHOR: SARITA THAKOOR**

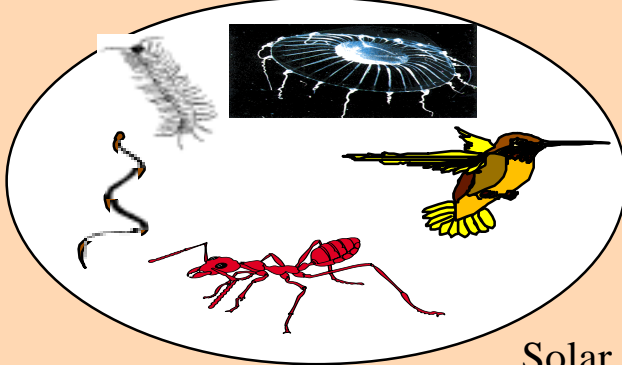
THE CHALLENGE TO OBTAIN A BIOMORPHIC ROBOT

- **NATURE'S CREATIONS**
 - **PRIMARILY ORGANICS BASED**
 - **EVOLUTION LED SURVIVING DESIGN AND MINIMALIST OPERATIONAL PRINCIPLES ARE INHERENT**
 - **GEOLOGICAL TIME SCALE HAS BEEN USED FOR EVOLUTION**
- **BIOMORPHIC ROBOT**
 - **PRIMARILY INORGANICS BASED, THE INGREDIENTS/MATERIALS AVAILABLE TO US**
 - **NEEDS TO BE CREATED BY DISTILLING THE PRINCIPLES OFFERED BY NATURAL MECHANISMS. CAPTURING THE BIOMECHATRONIC DESIGNS AND MINIMALIST OPERATION PRINCIPLES FROM NATURE'S SUCCESS STRATEGIES**
 - **DO IT WITHIN A LIFETIME**

BIOINSPIRED ENGINEERING OF EXPLORATION SYSTEMS

1st NASA/JPL Workshop on Biomorphic Explorers for Future Missions

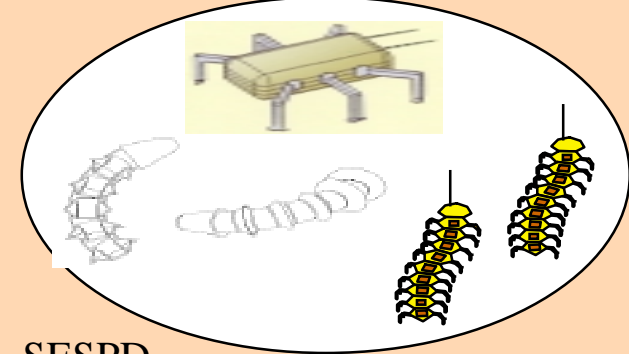
INSPIRATION



August 19 - 20, 1998
Jet Propulsion Laboratory
Pasadena, CA
Auditorium 180 - 101

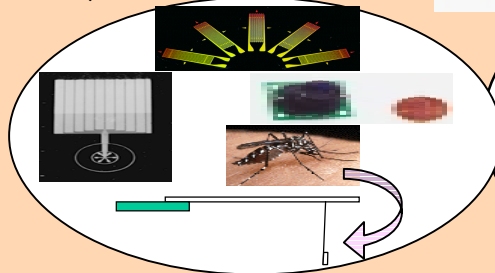
Sponsored by NASA/JPL
Solar System Exploration Program, SESPD
New Millennium Program, NMP
Space Mission Technology Development Program, TAP
Center for Integrated Space Microsystems, CISM

IMPLEMENTATION

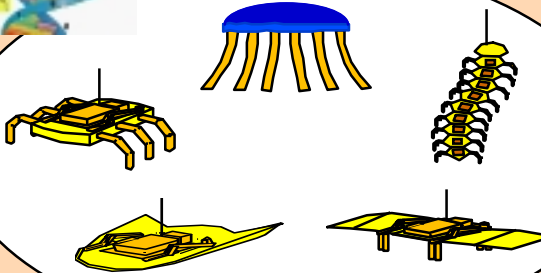


BIOMORPHIC CONTROL ALGORITHMS

μ SENSORS



ADVANCED MOBILITY



μ POWER

μ NAVIGATION

μ COMPUTING

μ COMMUNICATION TEMPERATURE CONTROL

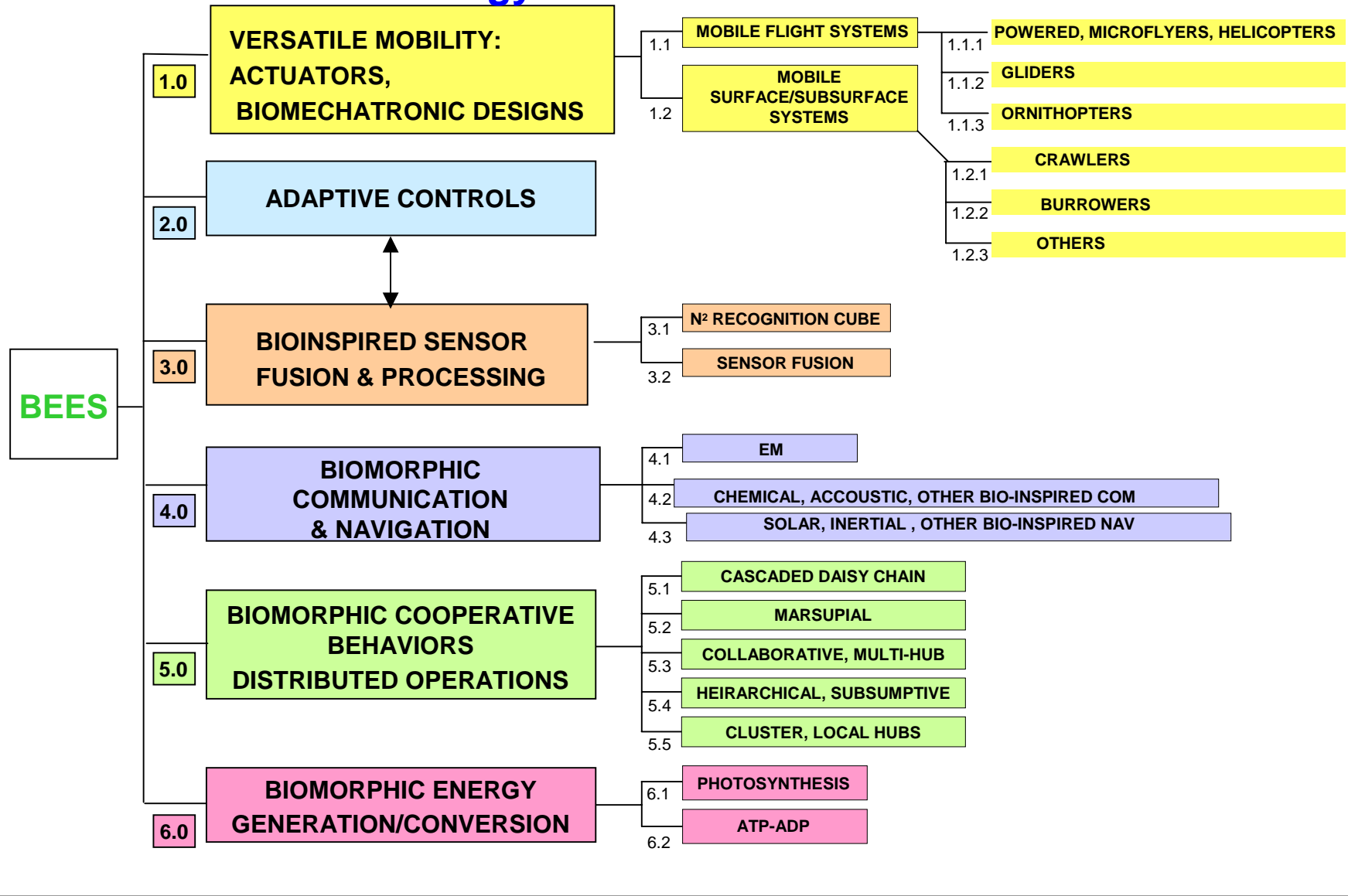
μ STRUCTURE

TECHNICAL POC: SARITA THAKOOR

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Bioinspired Engineering of Exploration Systems (BEES)

Technology Sub-Elements Breakdown



Biomorphic Explorers: Classification (Based on Mobility and Ambient Environment) Biomorphic Explorers

Aerial

Surface/Subsurface

Biomorphic Flight Systems

Biomorphic Surface Systems

Biomorphic Subsurface Systems



Seed Wing



Monarch Butterfly



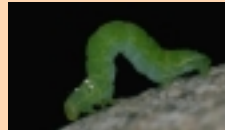
Soaring Bird



Humming Bird



Ant



Inchworm



Centipede



Earthworm



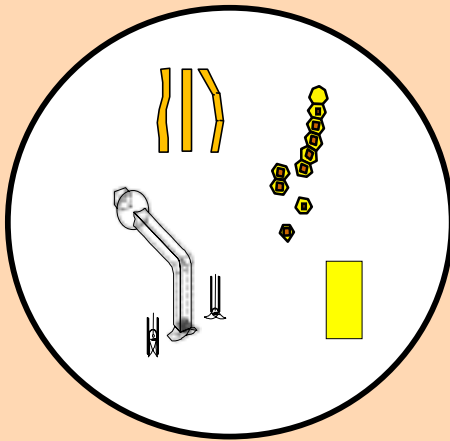
Germinating Seed



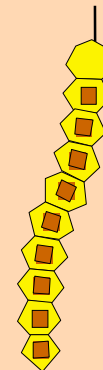
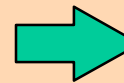
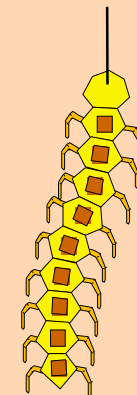
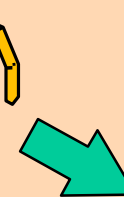
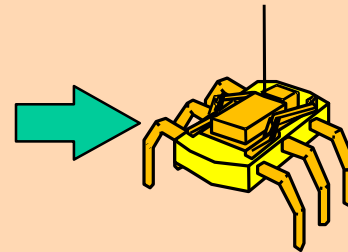
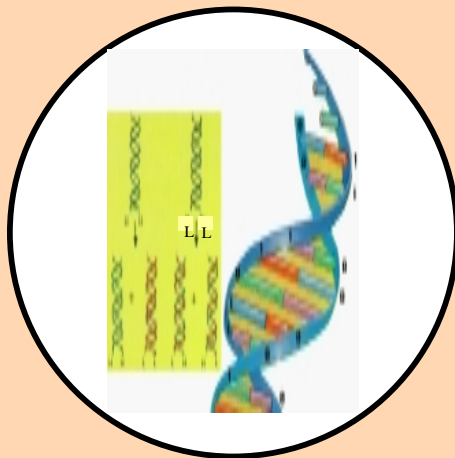
Snake

Examples of biological systems that serve as inspiration for designing the biomorphic explorers are illustrated. Pick a feature, say soaring, the intent is to make an explorer that combines the different attributes seen in nature in diverse species and capture them all in one artificial entity, in that sense the explorer goes beyond biology to provide us the adaptability that we need in encountering and exploring what's as yet unknown

Reconfigurable Mobile Units



Biomorphic Control



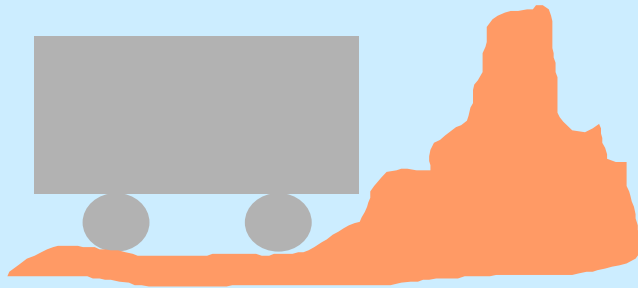
Biomorphic Explorers allow tailoring the best mix of tools for a specific function using a combination of all nature tested strategies employed by different biological organisms

MULTITERRAIN Biomorphic Explorer Bioinspired Sensor Fusion & Processing

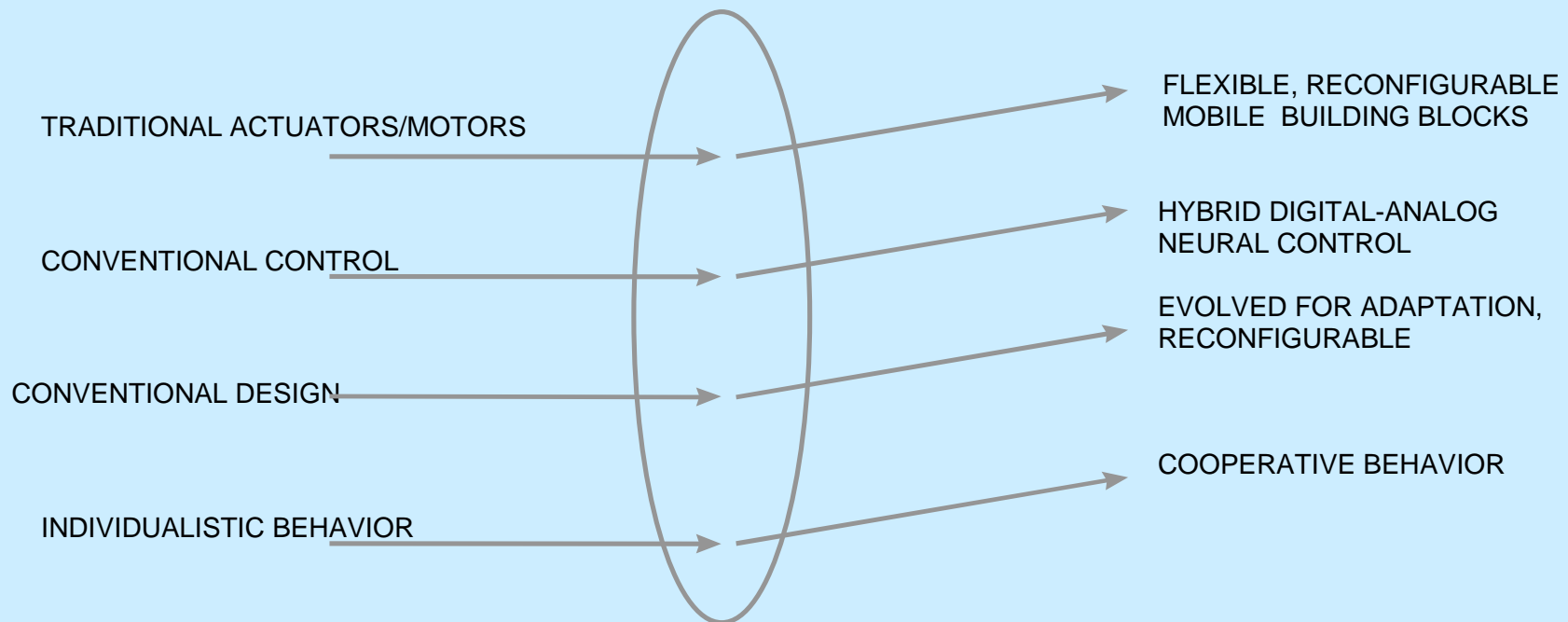
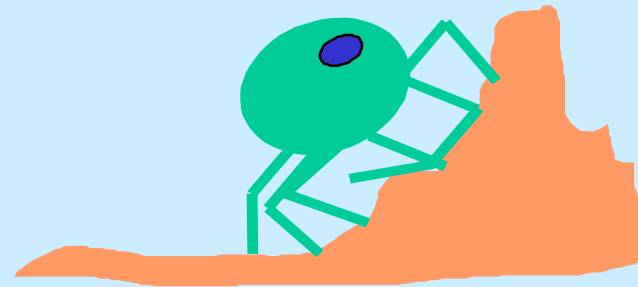
This development is geared towards the creation of a explorer which is capable of identifying its environmental condition/situation and adaptively changes its mobility mode to suit the prevailing/impending situation. For example if the terrain changes from hard and rocky to swampy slushy ground then the explorer changes from a small footprint pogo stick type mode to a duck feet like wide foot-print mode.

BIOINSPIRED ENGINEERING OF EXPLORATION SYSTEMS

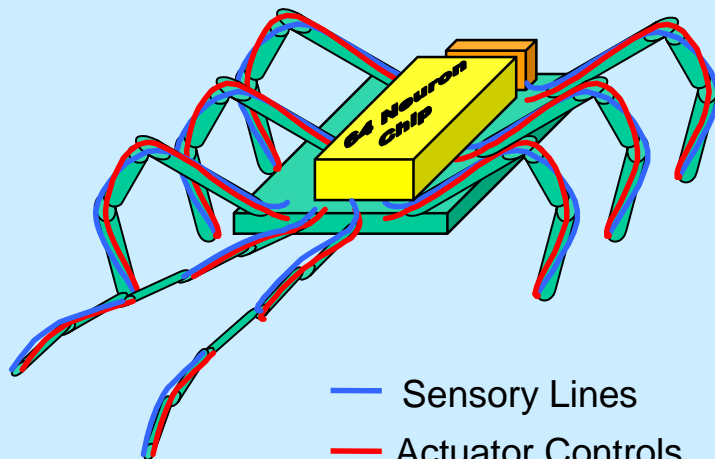
Current Rovers



Biomorphic Explorers

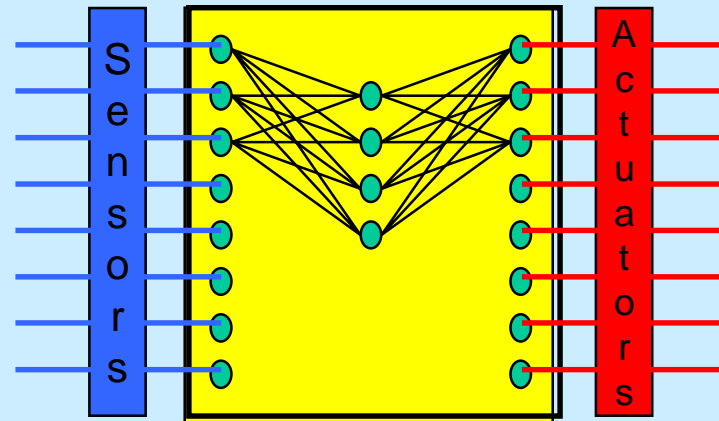


MULTITERRAIN Biomorphic Explorer



- Sensory Lines
- Actuator Controls

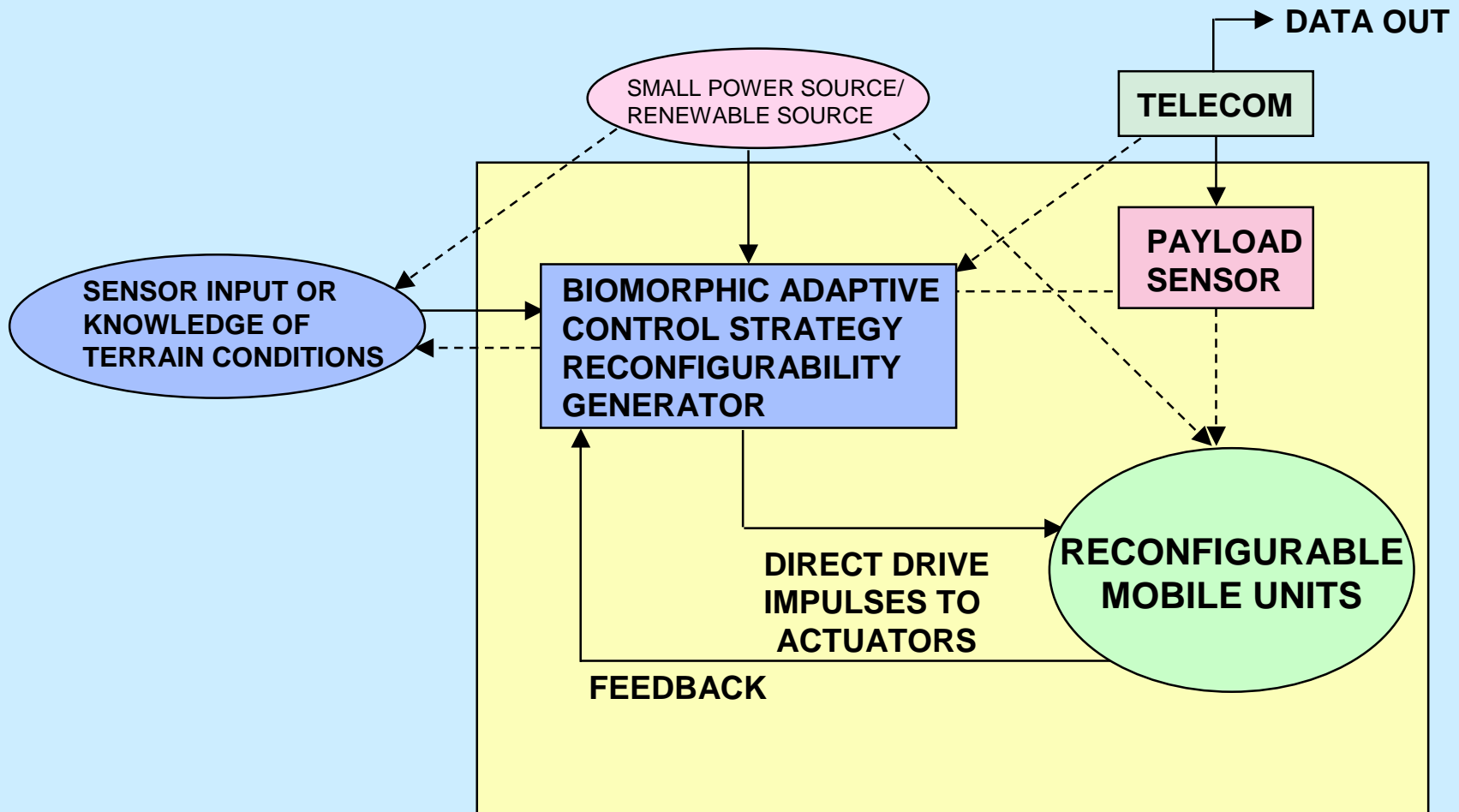
Neural connections mapped on 64 Neural Network (NN) Chip



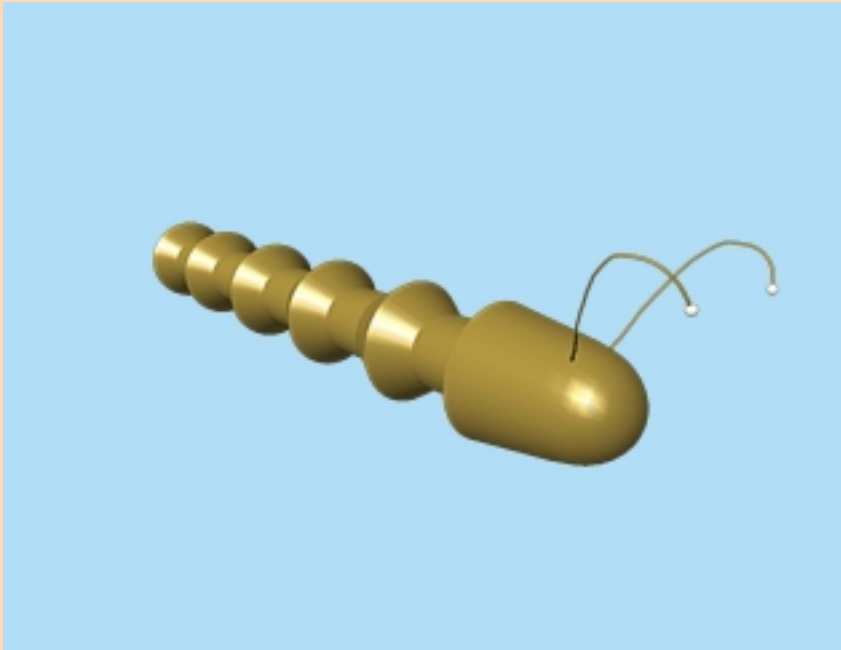
JPL's 64 NN chip characteristics:

- Low Weight (5 g)
- Small Size (1 cm x 1 cm)
- Low Power (12 mW)
- High Speed (~250 ns)
- Programmable Neural Network Architecture

Distributed Control Operational Schematic



Worm Robot for In-situ Exploration



EXTENDED CONFIGURATION



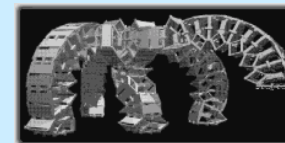
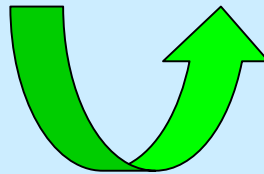
CONTRACTED CONFIGURATION

The worm robot conceptual design illustrated in the following slide and shown in animation is inspired by the technique used by an earthworm and inchworm. The mobile entity is composed of a series of modules where each module is capable of contracting or expanding and has anchors at each end. It anchors at the back end and expands fully, then it de-anchors the back end and anchors the front end and contracts again and re-anchors the back end. This wave of contraction/expansion and anchoring/de-anchoring proceeds continuously to achieve the forward motion. The animation shows, how such a worm would be capable of burrowing in sandy soil and entering narrow cracks in rocks for obtaining pristine samples from such hard to reach places.

BIOMORPHIC EXPLORERS: VERSATILE MOBILITY



**BIOLOGICAL EXAMPLE OF
RECONFIGURABLE MOBILE UNIT**

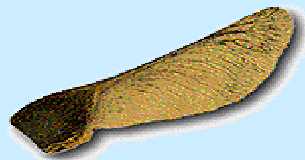
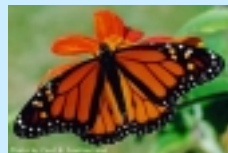


(Mark Yim, 1998)

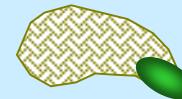
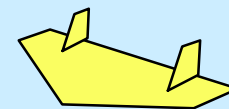
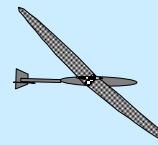
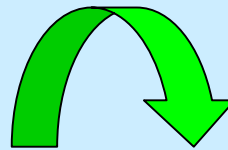


**CHALLENGE: TO DESIGN
RECONFIGURABLE MOBILE UNIT**

**SURFACE/
SUBSURFACE**



**BIOLOGICAL EXAMPLES OF
FLYERS**



**BIOMORPHIC FLIGHT SYSTEMS
• DOD LEVERAGE**

FLYERS

Biomorphic Explorers: Versatile Mobility

The surface/subsurface examples of versatile mobility discussed so-far are summarized in the top section of the following slide. The bottom section of the slide shows examples of biomorphic flight systems and their respective inspirations.

Biomorphic flight systems are attractive because they provide:

- Extended reach over all kinds of terrain
- Unique perspective for IMAGING, SPECTRAL SIGNATURE,
- Ability to perform distributed ATMOSPHERIC MEASUREMENTS
- Ability to Deploy/Distribute Payloads

Many biomorphic explorers(seedwing flyers, crawlers, burrowers, gliders etc)can work in cooperation with larger UXV'S to enable new missions and achieve successfully currently UNATTAINABLE MISSIONS

BIOMORPHIC EXPLORERS

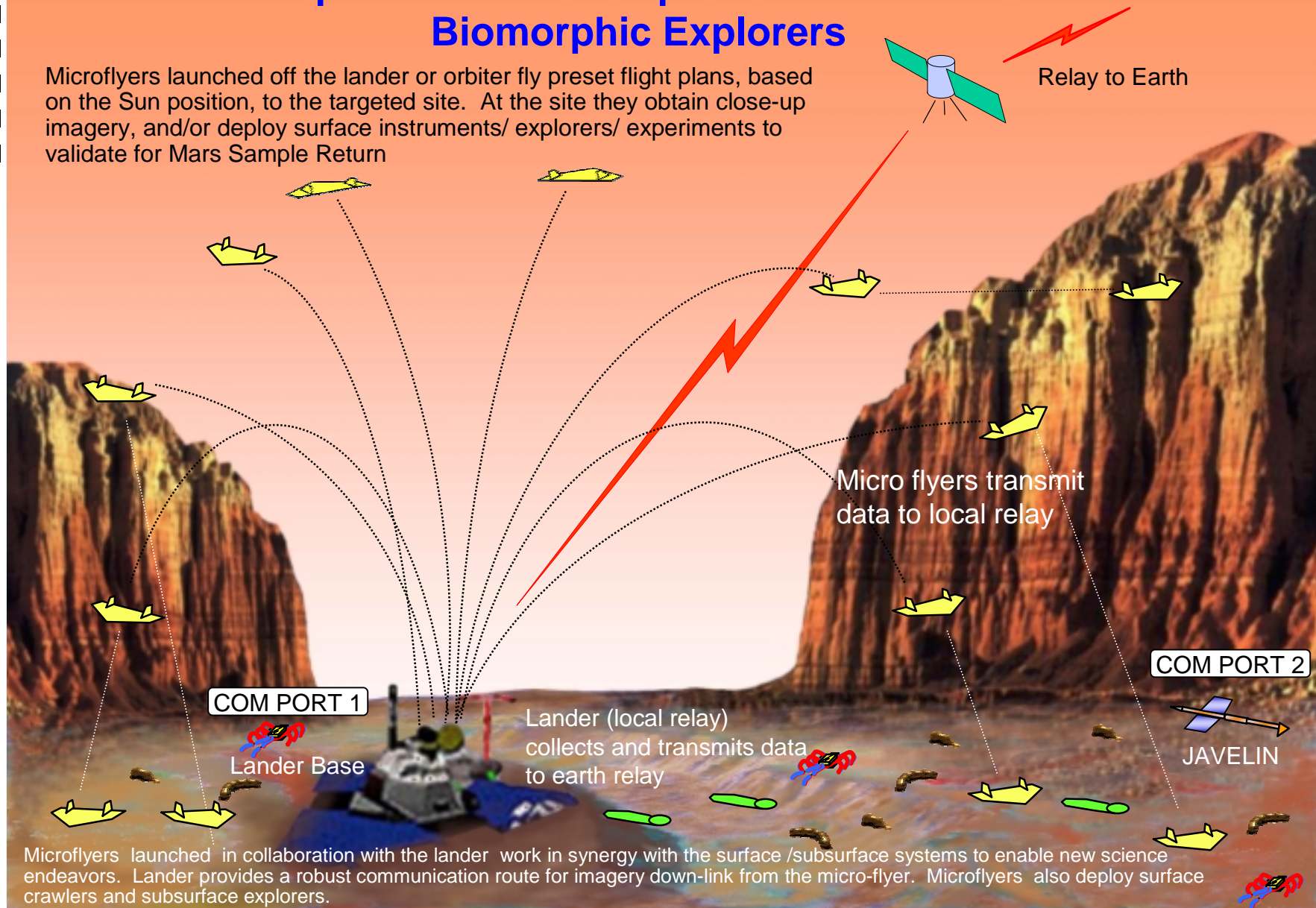
- Bio-morphic explorers constitute a new paradigm in mobile systems that capture key features and mobility attributes of biological systems, to enable new scientific endeavors.
- The general premise of biomorphic systems is to distill the principles offered by natural mechanisms to obtain the selected features/functional traits and capture the biomechatronic designs and minimalist operation principles from nature's success strategies.
- Bio-morphic explorers are a unique combination of versatile mobility controlled by adaptive, fault tolerant biomorphic algorithms to autonomously match with the changing ambient/terrain conditions.
- Significant scientific payoff at a low cost is realizable by using the potential of a large number of such cooperatively operating biomorphic systems.
- Biomorphic explorers can empower the human to obtain extended reach and sensory acquisition capability from locations otherwise hazardous/inaccessible

Biomorphic Missions

- Biomorphic Missions are co-operative missions that make synergistic use of existing/ conventional surface and aerial assets along with biomorphic robots.
- Just as in nature, biological systems offer a proof of concept of symbiotic co-existence, the intent here is to capture/imbibe some of the key principles/success strategies utilized by nature and capture them in our biomorphic mission implementations.
- Specific science objectives targeted for these missions include
 - Close-up imaging for identifying hazards and slopes,
 - Assessing sample return potential of target geological sites,
 - Atmospheric information gathering by distributed multiple site measurements, and
 - Deployment of surface payloads such as instruments/biomorphic surface systems or surface experiments.

Biomorphic Mission: Cooperative Lander/Rover - Biomorphic Explorers

Microflyers launched off the lander or orbiter fly preset flight plans, based on the Sun position, to the targeted site. At the site they obtain close-up imagery, and/or deploy surface instruments/ explorers/ experiments to validate for Mars Sample Return



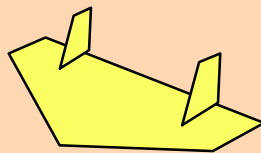
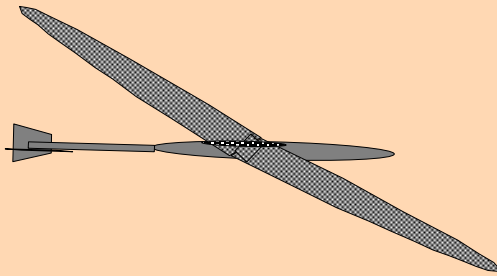
Microflyers launched in collaboration with the lander work in synergy with the surface /subsurface systems to enable new science endeavors. Lander provides a robust communication route for imagery down-link from the micro-flyer. Microflyers also deploy surface crawlers and subsurface explorers.

Surface Launched Microflyers: Options Comparison

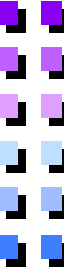
- **Contamination Free Launch options**
 - Spring launched (massive, KE left over, complex possibly damaging recoil)
 - Electric launch options (power hungry)
 - Electrically driven propeller (Mars atmosphere too thin)
 - Electromagnetic gun
 - Inflate and release a balloon (complicated mechanism, thin atmosphere a challenge, susceptible to winds)
 - Pneumatic, compressed gas launch (simple mechanism, simple recoil, leading candidate)
- **Rocket Boosted launch (contaminants, HCl, nitrates etc.) a good option for application such as scouting where contamination is not an issue**

Biomorphic Microflyers

- Small, simple, low-cost system ideal for distributed measurements, reconnaissance and wide-area dispersion of sensors and small experiments.
- Payload mass fraction 50% or higher.
 - small mass (100 g - 1000 g)
 - low radar cross section
 - larger numbers for given payload due to low mass
 - precision targeting to destination
 - amenable to cooperative behaviors
 - missions can use potential energy by deploying from existing craft at high altitude
 - Captures features of soaring birds, utilizing rising currents in the environment
 - Launch options: spring, compressed gas launch, electric, rocket boosted etc
 - *Adaptive Control, Adaptive Wings*
 - *Self Repair features*



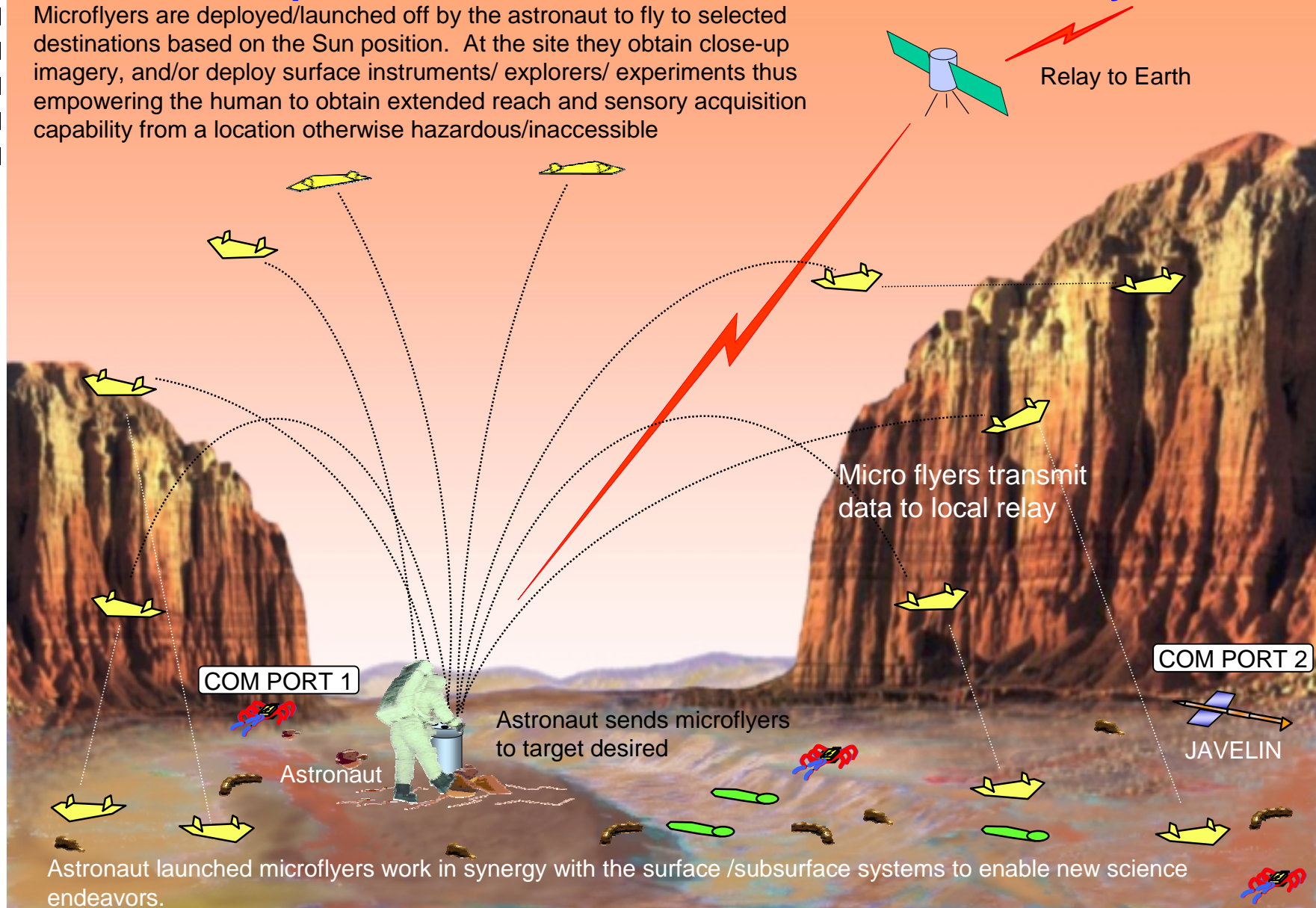
Biomorphic Mission - Time Steps

- **Near Term 2007 (Time Step 1)**
 - Image surface topography
 - Characterize terrain around lander
 - Identify rocks of interest for rover/lander
 - Distribution of Instruments/Experiments/Surface explorers to targeted sites
 - **2007 - 2009 (Time Step 2)**
 - Enable scouting, long range maps of areas of interest, and distributed deployment/in-situ measurements
 - Communication based on a self-organized, self-routing network, which is optimized dynamically using amorphous network of multiple hubs.
 - **Long Term 2011 and beyond (Time Step 3)**
 - Co-operative Operation of a multitude of Explorers together to obtain imagery, and deploy surface payloads, Reconnaissance Mission
 - Astronaut Launched Microflyers: empowering the human to obtain extended reach and sensory acquisition capability from locations otherwise hazardous/inaccessible
- 

BIOINSPIRED ENGINEERING OF EXPLORATION SYSTEMS

Biomorphic Mission: Astronaut Launched Micro-Flyers

Microflyers are deployed/launched off by the astronaut to fly to selected destinations based on the Sun position. At the site they obtain close-up imagery, and/or deploy surface instruments/ explorers/ experiments thus empowering the human to obtain extended reach and sensory acquisition capability from a location otherwise hazardous/inaccessible

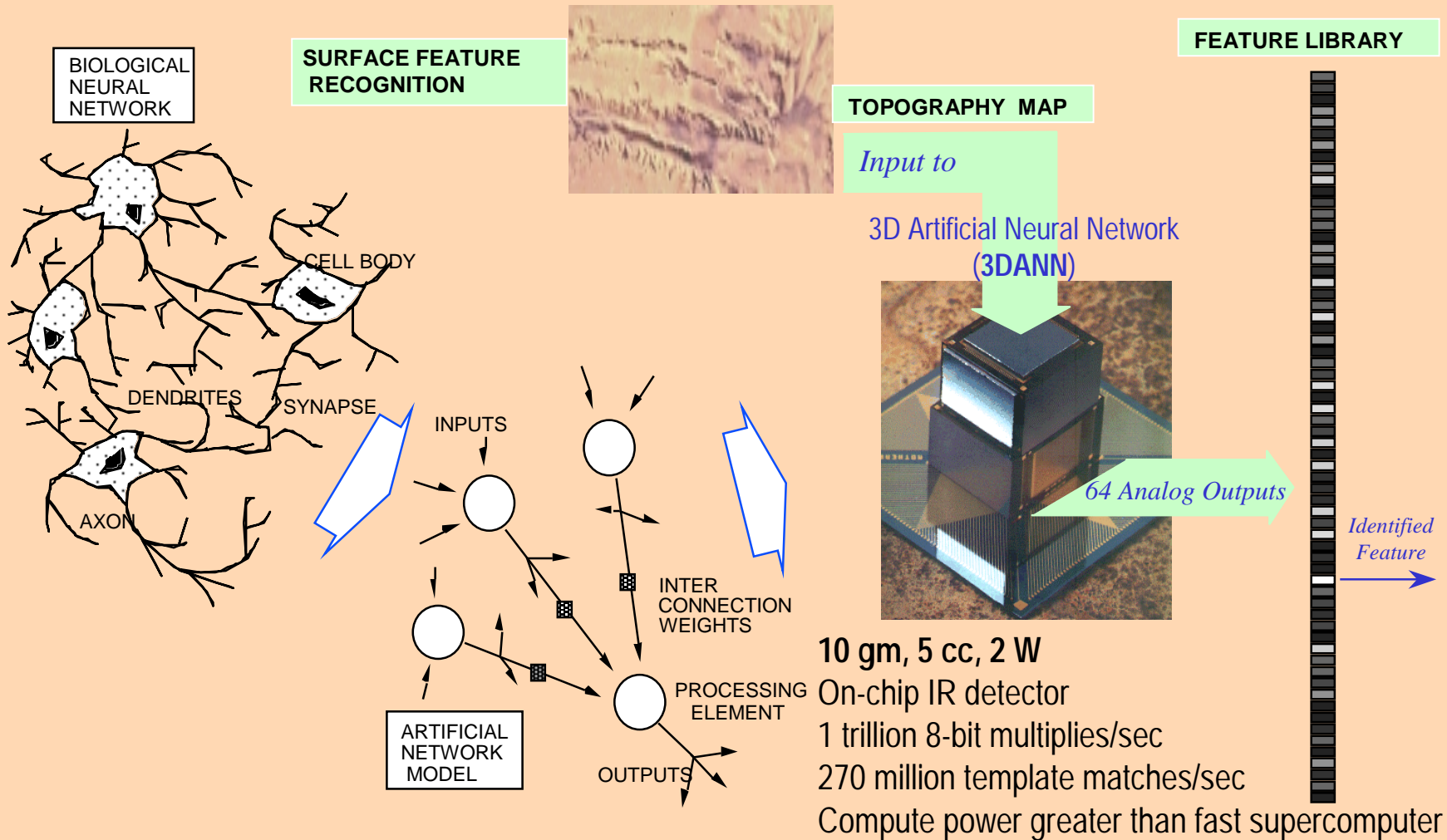


Astronaut launched microflyers work in synergy with the surface /subsurface systems to enable new science endeavors.

Enabling Processor for Surface Feature Recognition

Modeled after the massively parallel neural networks in human brain, 3DANN is a low-power, analog computing device capable of achieving human-like target recognition capability. The sugar-cube sized 3DANN processor has achieved an overall computing speed of ~ 1 trillion operations per second, consuming only ~ 8 watts of power (board (6W) + chip stack (2W)). This processing performance is ~ 3 orders of magnitude higher than the state-of-the-art image-processing on conventional digital machines (e.g. the Apple's recently introduced G4 computer which delivers ~ 1 billion operations per second, consuming ~ 200 watts of power). The processor can be trained to recognize geological features of interest and used to obtain real time processing of camera input imagery to identify surface features of interest. As a compact, low-power, intelligent processor on-board a space system, it would enable for the first time, real-time functions such as in-situ landing site selection with hazard avoidance, visual navigation, precision rendezvous and docking, and visually intelligent planetary robots/rovers capable of autonomous selection of scientifically interesting spots for maximum science return.

Enabling Processor for Surface Feature Recognition



JPL neural network chip design enables the 3DANN technology that delivers unprecedented processing speed for feature recognition (64 convolutions of 64x64 masks in 16 msec vs. 2 hours on state-of-the-art workstations)

Biomorphic Cooperative Behaviors

The behavior of ant colonies, specifically, how the ants coordinate complex activities like foraging and nest building, has fascinated researchers in ethology and animal behavior for a long time. Several behavioral models have been proposed to explain these capabilities. Algorithms inspired from the behavior of ant colonies have already entered into the mathematical field of multi-parameter optimization. Solar system exploration, particularly of Mars and certain planet/satellites, could be substantially enhanced through use of a multitude of simple, small, somewhat autonomous explorers that as a group would be capable of "covering" large areas. A fleet of such explorers would have some form of limited communication with a mother ship (a larger lander/rover or an orbiter). In many cases, cooperation among all the "fleet-mates" could greatly enhance group effectiveness. Our concept is geared to identify potential useful cooperative behaviors for such explorers by surveying emerging multirobot-multiagent techniques and by assessing some of the uniquely powerful examples of cooperative behavior and self-organization observed in nature, specifically in the insect kingdom.

Biomorphic Communication & Navigation

Honeybees are impressive in their ability to communicate precise navigational information. They use a recruitment dance and the sun as a celestial reference to communicate the location of a food source. Such principles related to planetary exploration could be utilized in a new class of small, dedicated, low cost biomorphic explorers.

Insects Operating Cooperatively

Nakamura and Kurumatani, 1995
Kubo, 1996

Ants' elaborate communication method with pheromone trails

Biomorphic Communication & Navigation



Karl von Frisch, 1965
Wehner and Rossel, 1985
Barbara Shipman, 1997
Srinivasan et al, 2000

Honeybee Inspired landing, terrain following, gorge following, obstacle avoidance and point-to-point navigation

Science Applications

- **ATMOSPHERIC INFO GATHERING**
- **DISTRIBUTED MULTIPLE SITE MEASUREMENTS**
- **CLOSE-UP IMAGING, EXOBIOLGY SITE SELECTION**
- **DEPLOY PAYLOAD: INSTRUMENTS/CRAWLERS**
- **SAMPLE RETURN RECONNAISSANCE**

Science Applications


... WHICH WOULD BE ENABLED/ENHANCED BY SUCH EXPLORERS.....

- VALLES MARINERIS EXPLORATION
 - ONE SINGLE SITE RICH IN GEOLOGIC UNITS
 - STUDY STRATIGRAPHIC COLUMN TOP TO BOTTOM ALONG THE CANYON WALL
 - OPTIMUM SCIENCE SAMPLE SITE
 - ... imager, temperature sensor, pressure sensor, sniffer: e-nose, individual gases, elements, etc.
- SCOUTING FOR CONDITIONS COMPATIBLE WITH LIFE TO LEAD US TO THE SPOTS THAT MAY HOLD SAMPLES OF EXTINCT/EXTANT LIFE
 - WIDE-AREA SEARCH WITH INEXPENSIVE EXPLORERS EXECUTING DEDICATED SENSING FUNCTIONS: close-up imaging!!!!
 - ... Individual gases, sniffer: e-nose, chemical reactions, pyrotechnic test, elements, specific amino acids, signatures of prebiotic chemistry, etc.
- GEOLOGICAL DATA GATHERING:
 - DISTRIBUTED TEMPERATURE SENSING
 - SEISMIC ACTIVITY MONITORING
 - VOLCANIC SITE
 - ... Multitude of explorers working in a cascade or daisy-chain fashion cooperatively to fulfill task

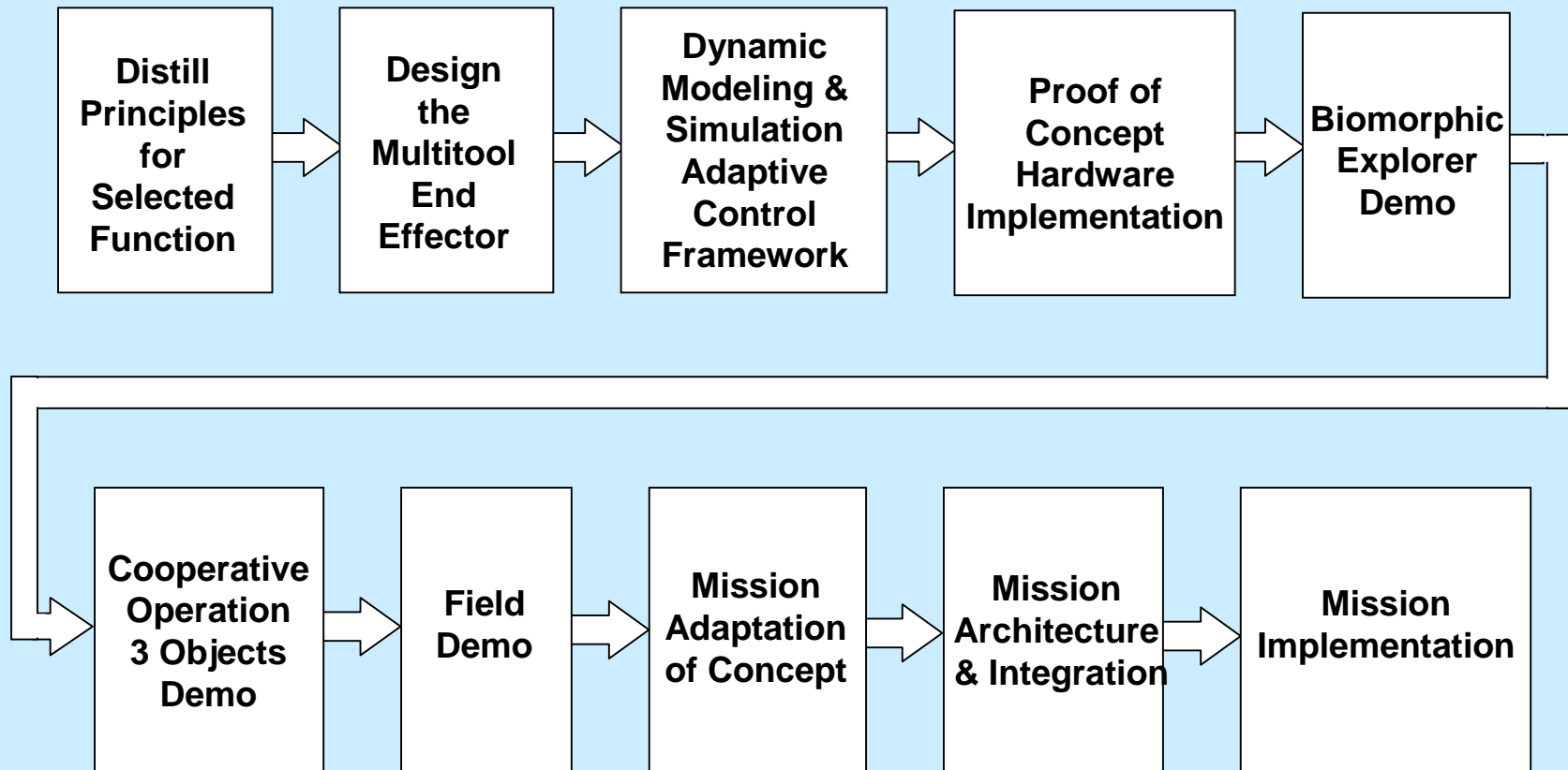
Applications (Dual Use NASA & DoD)

- Close-up Imaging, Site Selection
- Meteorological Events: storm watch
- Reconnaissance
- Biological Chemical Warfare
- Search and Rescue etc.
- Surveillance
- Jamming
- Distributed Aerial Measurements
 - Ephemeral Phenomena
 - Extended Duration using Soaring
- Delivery and lateral distribution of Agents (sensors, surface/subsurface crawlers, clean-up agents)

Biomorphic Missions

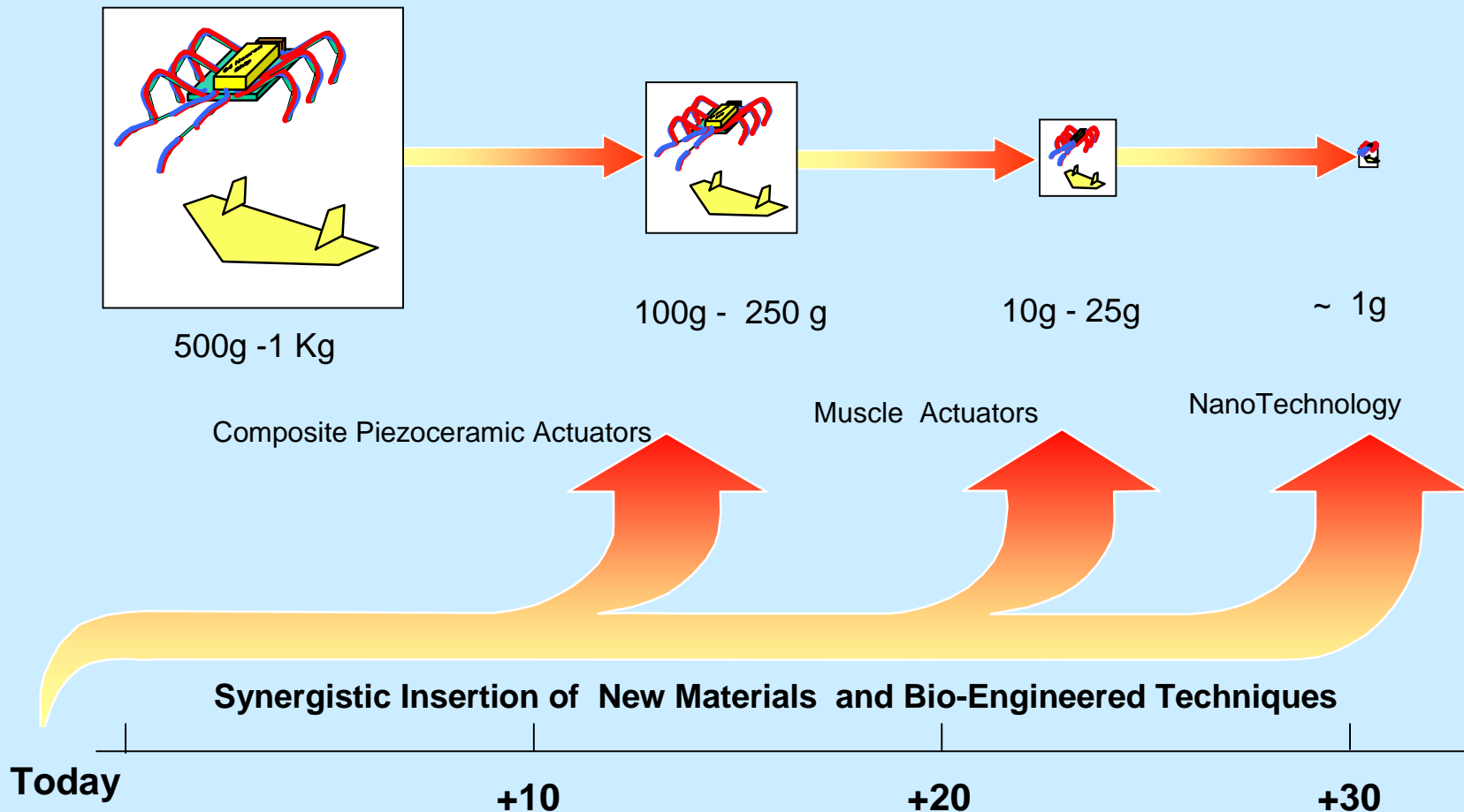
- **PAYOFF:**
 - **MULTIPLE USE NASA/DoD/NIH/NCI**
 - **BIOMORPHIC EXPLORERS, IN COOPERATION WITH CURRENT EXPLORATION PLATFORMS CAN ENABLE**
 - **EXPLORATION OF CURRENTLY INACCESSIBLE AND/OR HAZARDOUS LOCATIONS**
 - **MUCH BROADER COVERAGE OF EXPLORATION SITES**
 - **EXPLORATION AT LOWER COST**
 - **MINIATURIZED MICRO/NANO BIOMORPHIC EXPLORERS CAN BE USED FOR DETECTION/DIAGNOSIS/TREATMENT OF DISEASES AND AILMENTS OF HUMAN BODY NON-INVASIVELY AT LOW COST**
- 

ROADMAP to Realizing BEES



ROADMAP to Realizing BEES

Scaleable Design of Biomorphic Explorers lends it to easy insertion of new technologies and readily amenable to miniaturization



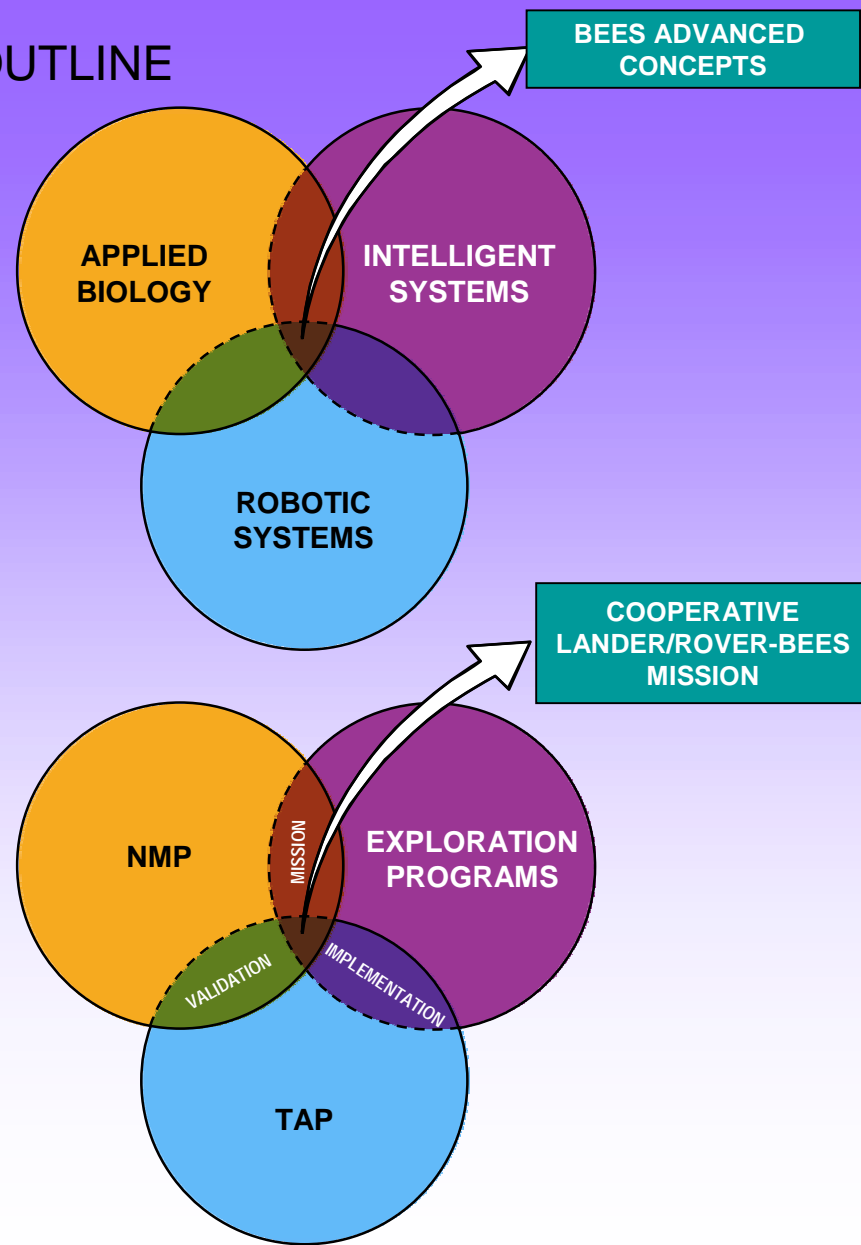
PROGRAM OUTLINE

SEEDING ELEMENT

- BEES ADVANCED CONCEPTS
 - NASA WIDE NRA TRL 0-3
 - WORKSHOP
 - UNIV/CALTECH GRADUATE PROGRAM, SURF PROGRAM
 - BEES SYSTEM DESIGN HUB

IMPLEMENTATION ELEMENT

- VALIDATION of INDIVIDUAL TECHNOLOGY SUB-ELEMENTS & MISSION CONCEPTS
 - NASA WIDE NRA TRL 3-5
 - GROUND VALIDATION OF BEES
 - BEES TEST BED
- DEMONSTRATION
 - (EXPLORATION PROGRAMS + NMP + TAP)
 - NASA WIDE AO TRL 6-7



BIOINSPIRED ENGINEERING OF EXPLORATION SYSTEMS

SUMMARY & ROADMAP: BIOINSPIRED ENGINEERING OF EXPLORATION SYSTEMS(BEES)
Enabling better spatial coverage and access to hard-to-reach and hazardous areas at low recurring cost

INSPIRATION

IMPLEMENTATION

BIOINSPIRED ADAPTIVE CONTROL

BIOINSPIRED NAVIGATION

μ SENSORS

μ COMMUNICATION

TEMPERATURE CONTROL

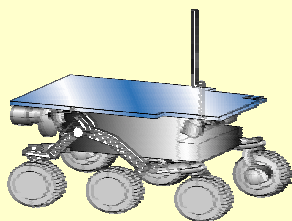
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BIOINSPIRED COMPUTING

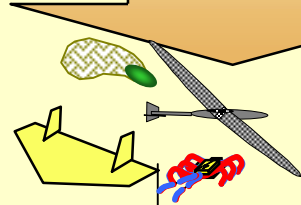
BIOMORPHIC COOPERATIVE BEHAVIOR

BIOINSPIRED MOBILITY

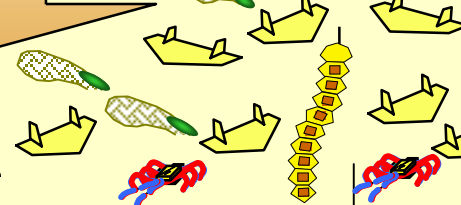
μ POWER



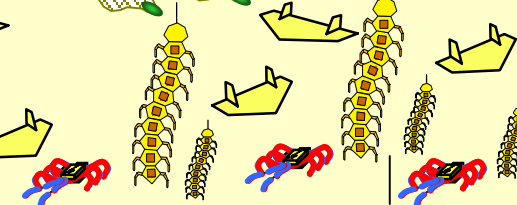
1997



2002



2007



2012

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